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Subsurface irradiance reflectance spectra of inland waters differing in morphometry and hydrology

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Abstract

A database has been established for relating subsurface irradiance reflectance, i.e. water 'colour', to the optical properties and water quality parameters of more than 120 Dutch inland water bodies. The concentrations of total chlorophyll-*a* (TChl-*a* = chlorophyll-*a* plus phaeopigment), total suspended matter and the Secchi-disc depth varied between 0.6 and 468 mg m⁻³, 0.8 and 98 g m⁻³, and 0.15 and 5.50 m, respectively. The water bodies represented very different water types based on morphometry and hydrology. The depth ranged from 0.4 to 40 m, and the surface area from 0.25 ha (fens in the moorland Peel) to 1200 km² (Lake IJsselmeer). The mean specific phytoplankton absorption coefficient at 676 nm was $0.013 \pm 0.003 \text{ m}^2 (\text{mg TChl-}a)^{-1}$. The absorption by tripton and dissolved humic substances at 440 nm varied between 0.1 and 16.4 m⁻¹, and 0.1 and 65.5 m⁻¹, respectively. By using the spectral position and magnitude of the subsurface irradiance reflectance peak alone, it was possible to distinguish groups of water bodies according to a classical typology based on morphometry and hydrology.

Introduction

The quality of surface water must meet an increasing number of environmental regulations, thus demanding intensive monitoring. Optical remote sensing from satellites and aircraft represents an innovative technique, which may provide an attractive addition for water boards to monitor water quality (Dekker et al., 1996). These techniques offer the possibility to obtain near-real time, full spatial coverage of water quality components. The maps of water quality parameters obtained in this way may be applied as one of the information layers within a Geographic Information System and, subsequently, be used in Decision Support Systems, providing a tool for integrated water management.

The colour of natural water is determined by changes in the spectral composition of the underwater light due to the optically active components in the water. The main components responsible are the phytoplankton, the non-living suspended matter (tripton),

the dissolved humic substances (DHS) and the water itself. The spectral changes in the underwater light with depth are due to absorption and scattering processes. By absorption light will be lost, and by scattering its direction changed. Water colour may be recorded as spectral reflectance, i.e. the ratio between the emergent light and the incoming light as a function of wavelength (Kirk, 1994). Reflectance spectra may be reconstructed via optical teledetection from satellites, aircraft or by using a field spectroradiometer.

A condition for successfully applying optical remote sensing techniques is the availability of adequate models or algorithms relating optical signature to water quality parameters. Since the early 1970's, empirical methods producing relative water quality maps have progressed towards (semi-) analytical methods producing absolute maps of water quality (Dekker et al., 1995). In this approach, physical relations are derived between water quality parameters, the underwater light field and the remotely sensed signal. Since the inherent optical properties (i.e. the absorp-

tion coefficient a , the scattering coefficient b and the volume scattering function $\beta(\theta)$, respectively) are physically related to the subsurface reflectance $R(0^-)$, this factor links the optical properties to the above the water surface remotely sensed signal. Relationships between reflectance and water quality parameters have general validity because $R(0^-)$ is relatively stable under varying solar angles, atmospheric conditions and states of water surface (Dekker et al., 1996).

Optical remote sensing techniques have been shown to provide reasonably accurate estimates of optical water quality properties such as concentrations of chlorophyll- a , c-phycoerythrin, suspended matter, and the vertical attenuation coefficient of downward irradiance (Dekker, 1993; Kirk, 1994). However, uncertainties exist about the validity of empirical and semi-analytic algorithms derived for particular areas or water types (Dekker, 1993; Dekker et al., 1995; Lathrop & Lillesand, 1986; Kirk, 1994). Algorithms have been developed for estimating a number of water quality parameters in oceanic (Case I) (Morel & Prieur, 1977; Viollier et al., 1980; Gordon et al., 1983) and coastal (Case II) marine (Gordon et al., 1983; Bricaud & Morel, 1986; Holligan et al., 1989) waters and in shallow, eutrophic lakes (Lathrop & Lillesand, 1986; Dekker et al., 1991; Mittenzwey et al., 1992; Dekker, 1993; Gons et al., 1997). For other important water types, as major rivers, such algorithms are still lacking.

As long as the relationships between the major structural components in the water and the inherent optical properties are not sufficiently known, a full analytical approach in algorithm development is not possible. A spectral library containing information about relationships between inherent optical properties and subsurface reflectance, and between the latter and the remote sensing signal will reduce the *in situ* measurements needed for model calibration (Dekker et al., 1995). Implicitly, such a spectral library will also provide the basis for developing an optical classification of water bodies.

The project 'Spectral library of Dutch waters' of the National Remote Sensing Programme in the Netherlands was performed in 1995. In this project, optical and water quality measurements were carried out simultaneously. More than 120 different locations, covering many inland and some tidal waters were visited between May and September 1995 (Figure 1). Since the study was aimed at obtaining a representative overview of the status of Dutch surface waters, most water types occurring in the Netherlands were included. Lakes

in the Provinces of Noord-Holland, Zuid-Holland, Utrecht, Groningen, Friesland, Limburg and Noord-Brabant were monitored. The data included all major lakes, and several different areas within the large Lakes IJsselmeer and Markermeer. Also former tidal waters in the Province of Zeeland and major rivers and canals were included in this study.

In this paper the Spectral Library database is described and a first attempt is made to relate the reflectance spectra to the various water types.

Materials and methods

General field protocol

The spectroradiometric measurement method used in the field and the calculations for obtaining the subsurface reflectance are described briefly (see Gons submitted, for details and theoretical background). Spectral subsurface irradiance reflectance $R(0^-)$ was assessed, by measuring radiance using a PR-650 spectroradiometer (Photo Research, Chatsworth, Ca, USA) held out from a boat or occasionally from a jetty or a bridge. At each radiance measurement cycle a dark measurement of equal duration was automatically subtracted. The integration time was automatically selected.

The water-leaving radiance (L_{au}) and the downward radiance of skylight (L_{sky}) were scanned at a nadir and zenith angle of 42° , respectively. The angle of 42° was used in order to avoid influence by reflection and shading from the boat. The measured water-leaving radiance includes reflected sky light, which can be subtracted after also measuring the sky radiance at the relevant angle (Equation (1)). In order to calculate downward irradiance (E_{ad}) and discriminate between direct sunlight and the diffuse irradiance, the radiance was measured from a calibrated reflectance panel before (L_{rp}) and after shading (L_{rpd}) (Equation (1)). For both practical and theoretical reasons the chosen direction of observation was 90° to the plane of the sun. Each scan involved 10 measurement cycles of which the average was filed. A complete series of scans was done in triplicate, which in general took less than 3 min.

Other parameters determined in the field were Secchi disc-depth, water depth, surface water temperature and local position. The position of the sample location was measured with a DGPS-device (SERCEL, France), with an accuracy of 2 m. Incidentally, the location was

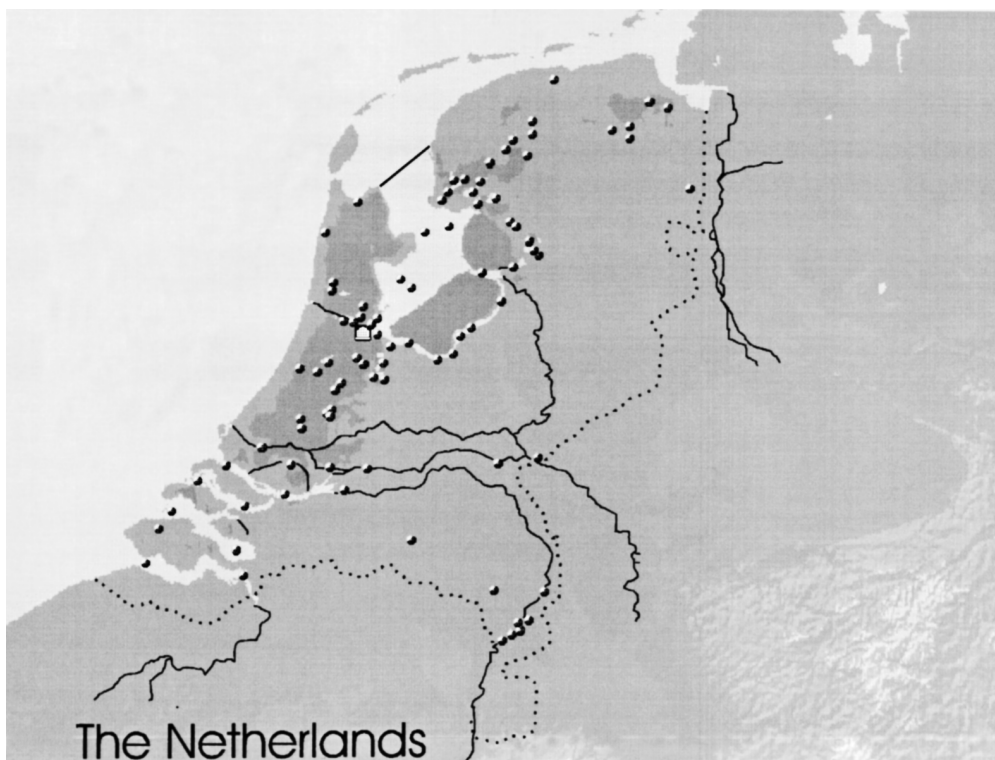


Figure 1. Map of the Netherlands indicating the study sites of the Spectral Library project in 1995. The special symbol refers to the city of Amsterdam.

recorded based on local maps. The starting times of the PR-650 measurements, cloud coverage and wave height were also noted.

Water quality data

Subsurface water samples (0.2 to 0.5 m depth) taken in 1-l bottles and placed in a cooler with melting ice were transported to the laboratory for analyses. The samples were processed immediately after arrival in the laboratory, where their temperature varied between 0 and 10 °C. Chlorophyll-*a* and phaeopigment were determined spectrophotometrically according to the Dutch standard method NEN 6520 (1981), by extraction in 80% ethanol at a temperature of 75 °C. The total chlorophyll concentration (TChl-*a*) is defined as the sum of Chlorophyll-*a* and phaeopigment.

The total suspended matter (TSM) concentration was measured after filtering samples over Whatman GF/F filters and drying the filters at 80 °C. Ignition loss was determined by ashing the filters with TSM at 550 °C. All analyses were performed in triplicates.

Inherent optical properties

The same water samples were used for determining spectra of absorption and beam attenuation using a Philips PU8800 UV/VIS double-beam spectrophotometer. The spectra were measured between 350 and 750 nm, at 1-nm intervals. The absorption of the dissolved humic substances (DHS) and the beam attenuation of the water sample were determined from optical density measurements in 5-cm sample cells. The DHS component of the water sample was obtained after filtration through a 0.45 µm Whatman GF/F filter. The data on beam attenuation are considered as preliminary results, since as they are yet not corrected for low-angle scattering.

Absorption spectra of seston (phytoplankton and tripton) and tripton were determined using the filterpad method (Trüper & Yentsch, 1967) with 0.45 µm Whatman GF/F filters. The absorption was calculated on a basis of a calibrated relationship between the optical density of a suspension in a sample cell and the optical density on a filter, see Weidemann & Cleveland (1993). The volume of water sample filtered was adjusted to

obtain an optical density on the filter between 0.4 and 0.5 at 440 nm. The absorption spectrum of tripton was obtained after extraction of the pigments from the filter (Kishino et al., 1985) using hot ethanol (80%, 75 °C). The extinction at 750 nm was subtracted from the entire spectrum, as a correction for residual scattering. The phytoplankton spectrum was derived by subtracting the tripton spectrum from the seston spectrum. The scattering coefficient b was estimated by subtraction of the absorption coefficients of seston, dissolved humic substances and water from the obtained beam attenuation coefficient. The scattering coefficients must also be considered as preliminary.

Subsurface irradiance reflectance

From the light measurements obtained with the PR-650 field spectroradiometer above the water surface, the subsurface irradiance reflectance $R(0-)$, i.e. the ratio of upward (E_{wu}) and downward irradiance (E_{wd}) just beneath the water surface, can be computed (see Gons, submitted for details). Calculation of the subsurface irradiance reflectance $R(0-)$ was carried out according to:

$$R(0-) = \frac{Q f (L_{au} - r_{sky} L_{sky})}{[\{ E_{ad} - r_{\theta} (1 - F) E_{ad} - r_{dif} F E_{ad} \} + (0.5 E_{wu})]} \quad (1)$$

where

Q = the conversion coefficient for L_{wu} to E_{wu} ,

f = the conversion constant of L_{au} to L_{wu} ,

L_{au} = the upward radiance above the water at nadir angle of 42°,

L_{sky} = the radiance of skylight at zenith angle of 42°,

r_{sky} = the Fresnel reflectance coefficient at zenith angle of 42°,

E_{ad} = the downward irradiance just above the water,

r_{θ} = the Fresnel reflectance coefficient for sunlight,

r_{dif} = the Fresnel reflectance coefficient for diffuse light,

F = the fraction diffuse light of E_{ad} ,

E_{wu} = the upward irradiance just below the water surface.

We applied the values $Q = \pi$, $r_{sky} = 0.026$, $f = 1.82$ or 1.84 (for freshwater (Dekker, 1993) and for salt water (Austin, 1980), respectively), and $r_{dif} = 0.06$ (Jerlov, 1976). The Fresnel reflectance coefficient for sunlight (r_{θ}) was calculated from Julian day, time and geographical position. The downward irradiance just above the water (E_{ad}) was obtained by measuring the radiance from a calibrated reflect-

ance panel. The fraction diffuse light (F) was the ratio between E_{ad} measurements obtained from the reflectance panel before (L_{rp}) and after shading (L_{rpd}).

The reflectance spectra were stored in the Spectral Library database in case they satisfied the following criteria:

(1) $R(0-) > 0$ for the spectral wavelength range between 440 nm and 780 nm, and

(2) $R(0-) < 0.33$ for the spectral wavelength range between 440 nm and 780 nm.

In case one of the triple $R(0-)$ spectra differed more than the standard deviation from the average, the spectrum was rejected. The two remaining $R(0-)$ spectra were averaged for use here.

Results

In the more than 120 inland and tidal waters surveyed in the summer of 1995, TChl-*a* varied between 0.6 and 468 mg m⁻³; TSM between 0.8 and 98 g m⁻³ and the Secchi-disc depth (Z_{SD}) between 0.15 and 5.50 m (Table 1). Based on morphometry the water bodies represented very different water types, with depths varying between 0.4 and 40 m. Also the surface areas ranged widely between 0.25 ha for fens in the moorland Peel and 1200 km² for Lake IJsselmeer.

Inherent optical properties

Inherent optical properties may be used as default input values in bio-optical modelling and in models for estimating water quality parameters. The absorption coefficient a and scattering coefficient b can each be partitioned among the major constituents. Except the spectral absorption and scattering of water (a_w and b_w), the partial coefficients of the other components are site-specific. They were averaged over all samples to obtain one set of representative values (Figure 2).

The spectral shape of the phytoplankton absorption (a_{ph}) depends on the phytoplankton species composition and distribution of the photosynthetic pigments in the cells (Kirk, 1994). The TChl-*a*-specific phytoplankton absorption coefficient (a_{ph}^*) at 675 nm varied between 0.007 and 0.107 m² (mg TChl-*a*)⁻¹. In this paper we rejected the values > 0.034 m² (mg TChl-*a*)⁻¹. In these cases, low chlorophyll to tripton ratio made the phytoplankton absorption determination unreliable. The mean TChl-*a*-specific absorption coefficient at 675 nm was 0.013 ± 0.003 m² (mg TChl-

Table 1. Ranges of concentrations of chlorophyll concentration (TChl-*a*; mg m^{-3}) and total suspended matter (TSM; g m^{-3}), Secchi-disc depth (Z_{SD} ; m) and absorption by dissolved humic substances (g_{440} ; m^{-1}) for the various water types. Average values are given in parentheses

Type	TChl- <i>a</i>		TSM		Z_{SD}		g_{440}		Number
Shallow L.	4–468	(102)	3–98	(28)	0.2–1.2	(0.5)	0.8–9.4	(3.6)	66
Cuts	4–344	(160)	2–53	(27)	0.2–0.8	(0.4)	5.4–16.5	(10)	12
Fens	142–273		9–37		0.2–0.3		17–66		2
Deep L.	1–76	(18)	1–14	(4)	0.6–5.5	(2.7)	0.1–4.9	(1.5)	11
Rivers	12–81	(31)	7–28	(17)	0.4–1.5	(0.7)	0.7–1.5	(1.0)	11
Canals	8–50	(26)	9–22	(16)	0.5–1.1	(0.8)	1.2–4.1	(2.2)	4
Ditches	56–63		21–27		0.5		8.2–9.0		2
Tidal W.	4–15	(8)	13–53	(33)	0.5–2.7	(1.5)	0.5–1.2	(0.7)	4

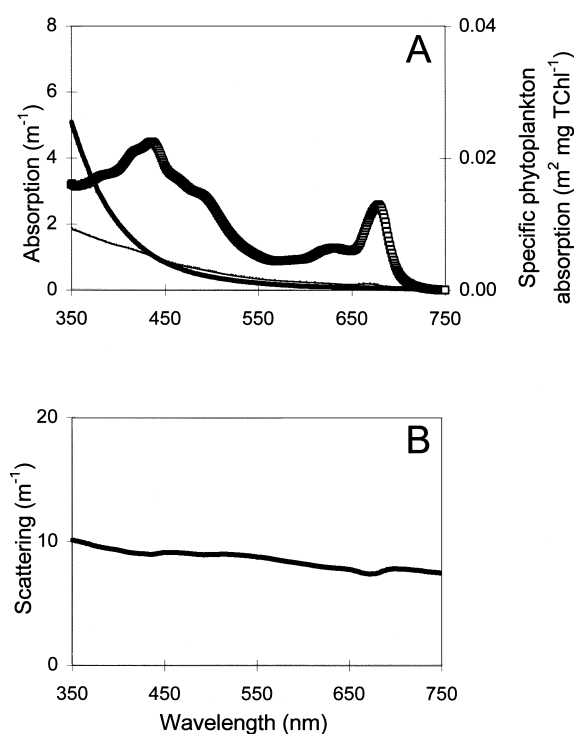


Figure 2. Spectral absorption and scattering averaged for all water types. (A) Absorption of tripton (thin line) and of dissolved humic substances (thick line) normalized to the values at 440 nm, and TChl-*a*-specific absorption of phytoplankton (symbols). (B) Scattering.

$a)^{-1}$. This value was comparable with the coefficients reported elsewhere (Kirk, 1975a, b; Morel & Bricaud, 1981; Davies-Colley et al., 1986; Maske & Haardt, 1987; Bricaud et al., 1988; Dekker, 1993).

The tripton absorption (a_{tr}) decreased steadily towards longer wavelength (Figure 2A), see also Kishino (1985) and Kirk (1994). Sometimes a shoulder due to breakdown products of photosynthetic pigments

occurred at the red waveband. The absorption of tripton is mainly by the detritus fraction, although inorganic particles may be coated with humic material and thus also contribute to absorption (Kirk, 1994). Tripton absorption at 440 nm varied between 0.1 and 16.4 m^{-1} . The variation in slope was small. The averaged slope of the tripton spectra, determined from 350 to 550 nm, was $0.009 \pm 0.001 \text{ nm}^{-1}$.

The DHS absorption (a_{ah}) showed a very strong exponential decrease towards the longer wavelengths, with low or zero absorption at the red end of the spectrum, typical for this component (Davies-Colley & Vant, 1987; Kirk, 1994). The absorption at 440 nm varied between 0.1 and 65.5 m^{-1} . The latter value, obtained for one of the fens in the Peel moorland is extraordinarily high. The averaged slope of the DHS spectra, determined for the interval 350 to 550 nm, was $0.016 \pm 0.002 \text{ nm}^{-1}$, i.e. the same as found for 40 locations in the Netherlands (Krijgsman, 1994). The value of 0.014 nm^{-1} has been used as default value in remote sensing applications for seawater (Bricaud et al., 1981; Kirk, 1994), but also other investigations demonstrated greater slope in freshwater lakes (Davies-Colley & Vant, 1987).

The averaged spectral scattering showed a slight decrease towards the longer wavelengths (Figure 2B). The values at 550 nm varied between 0.1 and 46.1 m^{-1} . The variation is explained by concentration, chemical composition and size of the particles (Kirk, 1994). As explained above, the averaged value at 550 nm of 8.8 m^{-1} may have been underestimated.

Reflectance spectra of different water types

The sample locations were classified following the definitions of the CUWVO Commission (1988), i.e.

mainly by morphometry and hydrology. In this paper the CUWVO types were translated into English as follows: 'meren' and 'plassen' as shallow lakes; 'petgaten' as cuts; 'vennen' as fens; 'zandwinplassen' and 'grindgaten' (sand and gravel pits, respectively) as deep lakes; 'rivieren' as rivers; 'kanalen' as canals; 'sloten' as ditches; 'getijdewateren' as tidal waters.

Spectral reflectance (Equation 2) is proportional to the ratio of spectral backscattering to spectral absorption of the water and its various particulate and dissolved constituents. Spectral reflectance peaks and local minima are inversely related to the sum of the absorption spectra for the phytoplankton, tripton, dissolved humic substances (Figure 2) and water (Buiteveld et al., 1994). In general reflectance peaks occurred around 550 nm, 650 nm and 700 nm, i.e. the wavelengths with a minimum in absorption. The first, often most prominent, peak followed upon strong absorption in the violet and blue wavebands by pigments (mainly chlorophyll-*a*), tripton and DHS. In many cases this peak was followed by a local minimum and secondary peak due to absorption by accessory pigments such as cyanophycocyanin (CPC). Above 550 nm, tripton and DHS generally played no dominant role in absorption (Figure 2). Around 675 nm the reflectance showed a minimum due to chlorophyll-*a* absorption. The decrease after the peak in the far-red spectral region is explained by increasing absorption of the water molecules with wavelength. The reflectance in the near-infrared is attributable to the scattering of the seston, since at wavelengths >750 nm only water is thought to significantly absorb the light.

Reflectance spectra were modelled on the basis of the spectral absorption and scattering (Gordon & Morel, 1983; Krijgsman, 1994). Impact of varying phytoplankton concentration on the reflectance peak height and wavelength in the 'average' shallow lake is illustrated in Figure 3. The backscattering albedo model (Krijgsman, 1994) appeared to be appropriate to model the reflectance of turbid, eutrophic waters:

$$R(0-) = r_i b_b / (a + b_b) \quad (2)$$

where b_b is the spectral backscattering coefficient, and the constant r_i is a function of the sun zenith angle and atmospheric conditions. We applied the averaged r_i value of 0.29 as established for 18 Dutch inland waters (Dekker, 1993), and assumed that the volume scattering function of Petzhold (Kirk, 1994) is also valid, so that b_b can be obtained as $0.019b$.

The spectral absorption was calculated as the sum $a = a_w + a_{ah} + a_{tr} + a_{ph}$, where $a_{ph} = a_{ph}^* \text{ TChl-}a$.

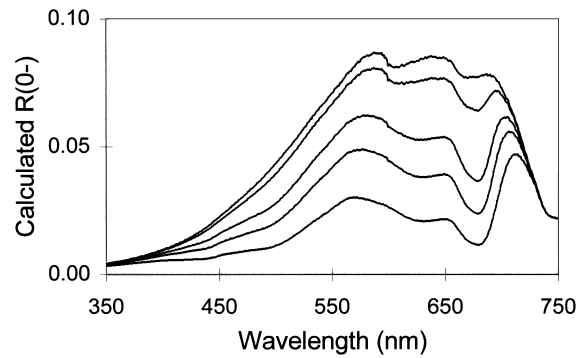


Figure 3. Modelled reflectance spectra for chlorophyll concentrations of 1, 10, 50, 100 and 250 mg m^{-3} , respectively. See text for further explanation.

The values of a_w were taken from Buiteveld et al. (1994) for a water temperature of 20 °C. The averaged spectral values for gilvin and tripton absorption and scattering, as obtained for the shallow lakes were kept constant, and the backscattering by phytoplankton was considered negligibly small compared to that by tripton (Kirk, 1994). The modelled reflectance spectra (Figure 3) showed the three characteristic peaks mentioned above. With increasing TChl-*a* concentration the first peak decreased and the wavelength changed from 588 nm to 572 nm. Both the peak at about 640 nm and the far-red peak shifted towards longer wavelengths. The far-red peak clearly evolved due to increase in chlorophyll-*a*. This simple way of modelling the reflectance using the inherent optical properties is of paramount importance to analyze shapes of the spectra in dependence of concentrations of the major constituents of the water (Dekker et al., 1994).

In Figure 4 the reflectance spectra for six of the distinguished water types are shown. The reflectance spectra of shallow lakes were characterized by two or three reflectance peaks. If not by a clear secondary peak, absorption by accessory pigments around 620 nm was apparent at least by the presence of a shoulder. A large number of shallow lakes showed the major peak in the far-red to near-infrared instead of the green to yellow waveband.

Spectral shapes in deep lakes and shallow lakes were similar, but the reflectance tended to be lower at all wavelengths, which can be attributed to lower suspended matter concentrations and thus lower scattering (Table 1). Only in two cases the greatest peak occurred in the far-red to near-infrared waveband. The reflectance spectra for the cuts (i.e. narrow elongated and shallow strips of water originating from peat-mining)

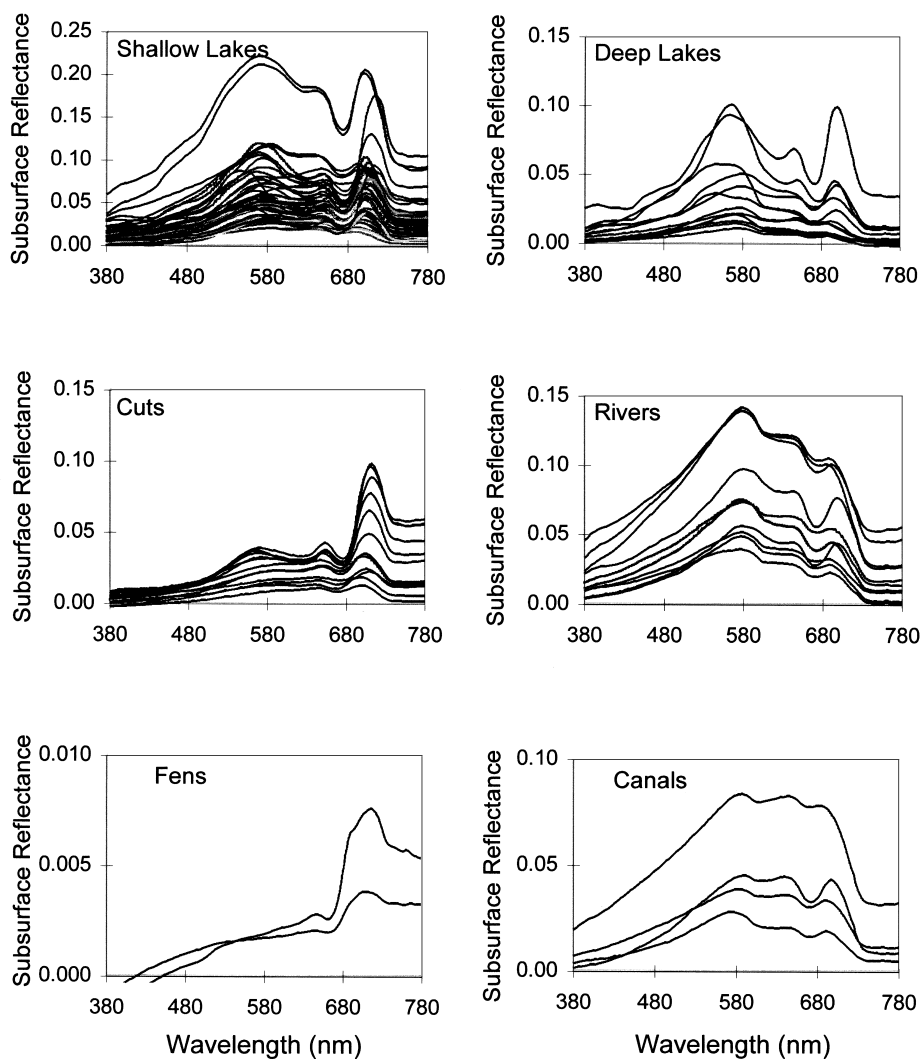


Figure 4. Subsurface irradiance reflectance spectra of the various water types.

were characterized by very low values at wavelengths < 600 nm, due to high absorption by dissolved humic substances (Table 1). The reflectance peak invariably occurred at around 700 nm. An even stronger shift to the near-infrared was found for the fens where, compared with all other water types, extremely high DHS concentrations were measured. Very little visible light escaped from these waters. Rivers and canals showed rather flat spectra between 500 and 700 nm and all of them had the reflectance maximum in the green to yellow spectral region. In the violet waveband their reflectance was rather high, since concentrations of DHS were relatively low in these water bodies (Table 1). The two ditches (not shown) exhibited

similar reflectance patterns as the shallow lakes. The spectra of the tidal waters (also not shown) resembled those of rivers and canals.

As a first step in analysing the spectral subsurface reflectance in relation to water types, we considered the wavelength and magnitude of the reflectance maximum. It appeared that the peak was positioned in either the green to yellow (i.e. 544 to 592 nm; G-peak; Figure 5A) or in the far-red to near-infrared region (i.e. 692 to 716 nm; R-peak; Figure 5B). In this respect alone, some of the CUWVO-defined water types appeared as distinct groups. The rivers showed peaks in the narrow interval 576–580 nm. The tidal waters exhibited maxima at 572 nm, with the exception of the West-

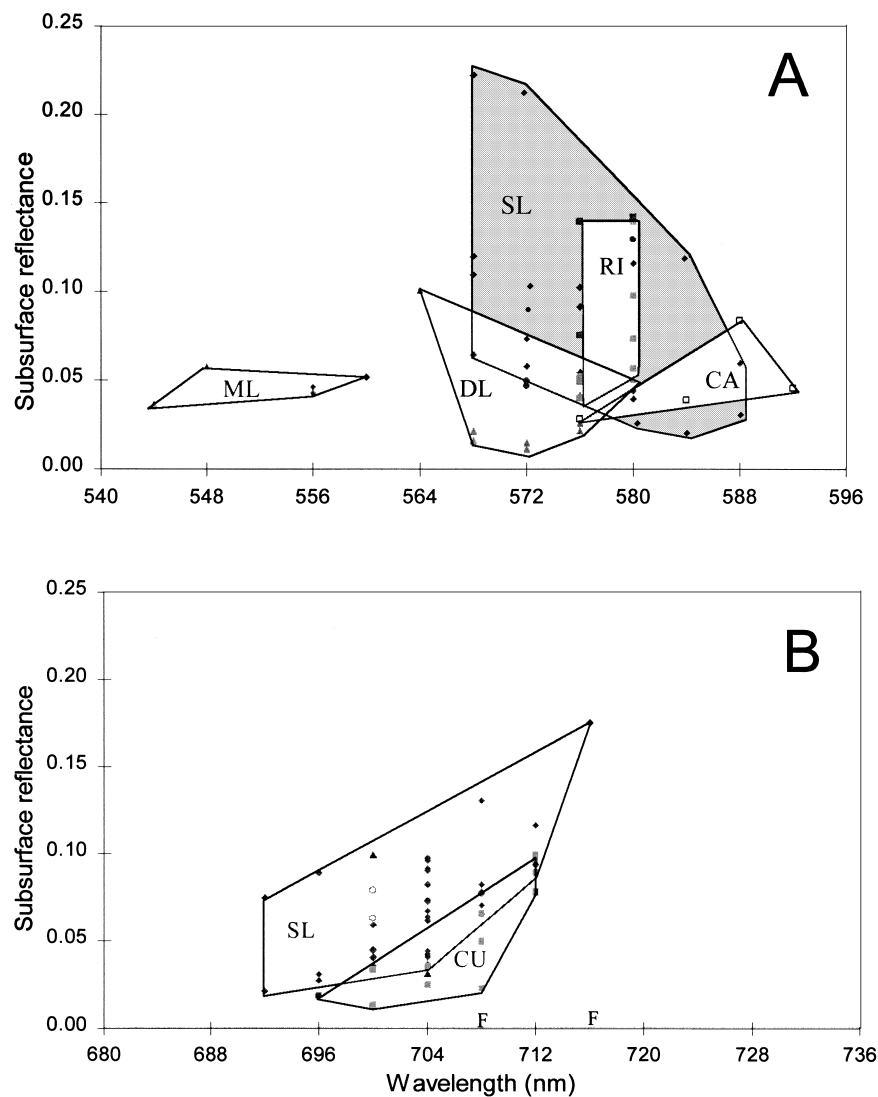


Figure 5. Wavelength and magnitude of the subsurface reflectance maximum found in either the green to yellow (A) or the far-red to near-infrared spectral region (B). Distinguished groups are: shallow lakes (SL), lakes connected to the River Meuse (ML), rivers (RI), canals (CA), deep lakes (DL), cuts (CU), and fens (F).

ern Scheldt station (Schaar van Ouden Doel), which had a peak location similar to those in the rivers. The sampling site was located near the entrance of the River Scheldt into the Western Scheldt Estuary and is thus periodically strongly influenced by river water. The highly turbid canals tended to have maximum reflectance at somewhat longer wavelengths than the rivers and thus formed a separate group, although the relatively clear North Sea Canal water showed a peak wavelength that was typical for the rivers.

The deep lakes, Spiegelplas and Kleine Vinkeveense Plas exhibited a R-peak. All other deep lakes showed G-peaks, but the wavelength tended to be shorter than in the rivers and canals. In this group the peak-wavelength range was quite broad. A distinct subgroup were the lakes connected to the river Meuse, which showed remarkably short peak wavelengths, i.e. ≤ 560 nm. The remaining group exhibiting G-peaks comprised part of the shallow lakes. This large and diverse group showed almost complete overlap with the rivers, tidal waters, and canals. The shallow lakes ten-

ded to have considerably greater reflectance peaks than the deep lakes, and like the cuts and fens, many shallow lakes exhibited a R-peak (Figure 5B). The shallow lakes showed a distinct trend of increasing peak height with its wavelength (cf. Figure 3). Both locations in the ditch Polderhoofd kanaal fell within the group of shallow lakes, which may be attributed to their waterflow connecting two eutrophic shallow lakes. The cuts were on average clearly recognizable from the shallow lakes by combination of low reflectance at wavelengths < 680 nm with a marked peak at around 700 nm. In this group the peak height also tended to increase with the wavelength of the peak. The two fens showed very low R-peaks at extraordinarily long wavelengths.

Discussion

Reflectance spectra of different water types

The use of magnitude and wavelength of the reflectance peak to define different optical water types has to be considered as a first, but promising step. This simple approach has already indicated that distinct optical water types can be detected which are connected to the morphometric and hydrologic properties as defined by CUWVO (1988). In order to more fully explain the different optical types, we must know not only the spectral absorption and scattering properties of the various components in the water, but also how nutrient loading and hydraulics affect the concentrations.

In shallow lakes two separate, broad groups of dominant reflectance were found: one group exhibited maximum peaks in the green to yellow (G-peak) and the other in the far-red to near-infrared spectral region (R-peak). The great variation in concentrations of phytoplankton and tripton appears to be especially important in shallow lakes, which showed a broad range of concentrations of chlorophyll and total suspended matter. Many of these lakes are eutrophic, and wind-induced resuspension of bottom material and detrital particles is very strong (Gons et al., 1991). The range in DHS concentration is also quite broad, depending on the regional substratum (e.g. peat vs. sand) and on hydrology. Therefore, the CUWVO type 'shallow lakes' is optically extremely heterogeneous. Increase in chlorophyll concentration alone may explain a spectral shift from dominating reflectance in the yellow waveband towards the near-infrared spectral region (Figure 3).

The lakes situated in the R-peak group, indeed, showed a wider range of chlorophyll concentrations and high average value (136 mg TChl-*a* m⁻³) than the lakes having a G-peak (50 mg TChl-*a* m⁻³). Furthermore, the mean DHS concentration (defined as *g*₄₄₀) was higher for the R-peak group (4.6 m⁻¹) than for the G-peak group (2.2 m⁻¹). Other studies have also demonstrated that the wavelength of the R-peak is coupled to the concentration of chlorophyll (Gitelson, 1992; Gons, submitted) and of DHS and tripton (Dekker, 1993).

The peak reflectance in the cuts was in the far-red to near-infrared spectral region. This group showed great variation in peak wavelength as well as in chlorophyll and DHS concentrations. Cuts originating in peat dredging were characterized by high DHS concentrations. Only in a few cases wind resuspension of sediment may be important, since the cuts are elongated, narrow strips of water, and therefore less wind-exposed than the shallow lakes. The two fens showed R-peaks at extremely long wavelengths. The peak position is clearly due to high chlorophyll concentration in combination with very high DHS concentration.

In deep lakes, the ranges in concentrations of chlorophyll and total suspended matter are less wide compared with the shallow lakes. In addition, the average values are much lower (18 mg TChl-*a* m⁻³ and 4 g TSM m⁻³). Due to water depth, wind resuspension is not as extensive as in the shallow lakes. Complete mixing of these lakes, and thus large-scale inputs of bottom material into the surface water, occurs only twice a year. Inputs of nutrients, DHS and mineral particles are relatively small during the summer stratification, and the tripton is dominated by detritus particles. Contrary to the other deep lakes, the lakes Spiegelplas and Kleine Vinkeveense Plas exhibited a R-peak instead of a G-peak. In L. Spiegelplas the location in the far-red may have been due to chlorophyll stratification. Chlorophyll concentrated at a depth of about 3 m can be detected by the PR-650 measurements, but of course not in the sample from <1 m depth. In L. Kleine Vinkeveense Plas the R-peak was only just greater than the G-peak, and caused by a bloom of *Microcystis*, the colonies of which were clearly visible.

A distinct subgroup of lakes, which are connected to the river Meuse, are flushed with river water and are often deepened by sand and gravel excavation. Silt from the river water will sink down, causing the relatively low reflectance of the lake water. The reflectance of these lakes showed a remarkably short green peak wavelength, which appeared to be explained by

a secondary absorption peak at about 560 nm. This absorption peak might be due to phycoerythrin being the major accessory pigment in the cyanobacteria in these lakes. Only L. Asseltse Plas showed a typical river spectrum, but this lake has much greater inflow of the R. Meuse compared with the other lakes.

The rivers and canals showed G-peaks, which for rivers tended to be far greater than that in the far-red region, but for canals the difference was rather small. These waters showed relatively low concentrations of chlorophyll but high suspended mineral concentration, which depends on several factors (stream velocity, the materials of the river bed, and resuspension by boats) and, therefore may greatly vary. Tidal waters also showed reflectance maxima in the green to yellow waveband. Their spectra, of course, will strongly depend on proportions of sea and river water.

Optical classification of Dutch inland waters

The data has been collected to create a large database for support and validation of analytical forward and inverse modelling of optical remote sensing for water quality monitoring. Successful modelling requires a reliable, extensive database covering broad ranges in the values of water quality parameters and water types. The data described here covered most of the important water bodies in the Netherlands and showed a wide variation in chemical and physical characteristics (Figure 1; Table 1). Implicitly, the work was aimed at developing an optical classification of Dutch waters. Optical classification of surface water is important since inland waters are highly diverse, and it is doubtful as to whether single algorithms for remote sensing of parameters like chlorophyll concentration can be applied. Algorithms specific for optically defined water types are expected to prove more reliable for estimating water quality parameters than 'universal' algorithms. Optical typology may therefore provide the basis for new algorithm development for water bodies differing widely in the inherent optical properties. Modelling reflectance spectra based on the inherent optical properties as shown in this paper is expected to explain the variability in the spectral reflectance in general and establish limits between which spectral characteristics may vary in particular water types.

This work has shown that the distinction of subsurface irradiance reflectance spectra on the sole basis of peak height and wavelength was connected to the classical typology according to morphometry and hydrology. However, to fully exploit the information and

establish a comprehensive and distinctive optical typology the reflectance spectra must be analyzed by using statistical approaches like PCA and cluster analyses. This approach is promising for linking reflectance spectra to functioning of aquatic ecosystems, including their response to environmental changes. That the rapid advances in remote sensing techniques will promote the use of spectral reflectance characteristics as parameters for monitoring water quality is a logical development.

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